

The DMTPC project

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for the DMTPC Collaboration

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Abstract. The DMTPC detector is a low-pressure CF_4 TPC with optical readout for directional detection of Dark Matter. The combination of the energy and directional tracking information allows for an efficient suppression of all backgrounds. The choice of gas (CF_4) makes this detector particularly sensitive to spin-dependent interactions.

1. Directional Dark Matter detection

The goal of a directional Dark Matter detector [1] is to provide an unambiguous observation of Dark Matter (DM) by measuring both the direction and the energy of the nuclear recoil produced by the interaction of a Weakly Interacting Massive Particle (WIMP) with a nucleus in the active mass of the detector.

The simplest models of the distribution of WIMPs in our Galaxy suggest that the orbital motion of the Sun about the Galactic center will result in an Earth-bound observer to experience a WIMP wind with speed 220 km/s (the galacto-centric velocity of the Sun) originating from the direction of the Sun's motion. Because the Earth's rotation axis is oriented at 48° with respect to the direction of the WIMP wind, the average direction of DM particles recorded by an Earth-bound observer changes by about 90° every 12 hours [2]. The ability to measure such a direction would provide a powerful suppression of insidious backgrounds such as cosmogenic neutrons and neutrinos from the Sun [3], as well as a unique instrument to test local DM halo models [4, 5]. This capability makes directional detectors unique observatories for underground WIMP astronomy.

Dark Matter interactions in the detector generate nuclear recoils with typical energies of few tens of keV (Fig. 1, left). The direction of the recoiling nucleus encodes the direction of the incoming DM particle (Fig. 1, right). To observe the daily modulation in the direction of the DM wind, an angular resolution of $\approx 30^\circ$ in the reconstruction of the recoil nucleus is required.

Directional DM experiments use low-pressure (40–100 torr) gas as target material, in which typical DM induced nuclear recoils have a length of a few millimeters. A 3-D reconstruction of the recoil track with a spatial resolution of several hundred microns in all three coordinates is sufficient to achieve the desired angular resolution. A 2-D reconstruction is still valuable,

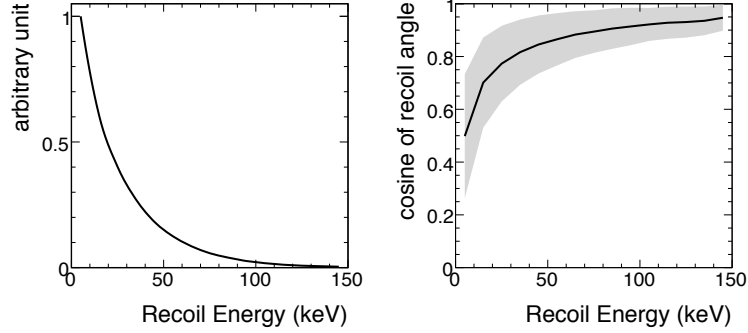


Figure 1. Energy spectrum and distribution of the cosine of the recoil angle vs. recoil energy for fluorine recoils induced by 100 GeV WIMPs in CF_4 . The recoil angle is defined as the angle between the direction of the recoil and the direction of the incoming particle.

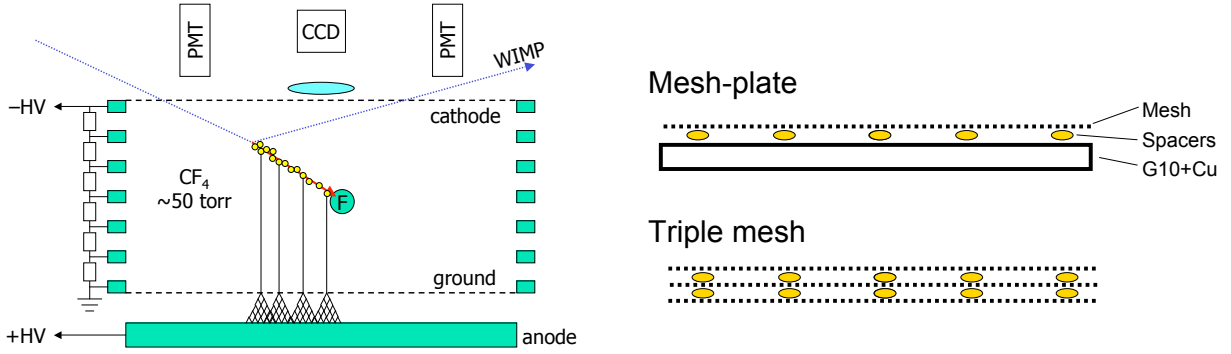


Figure 2. Left: illustration of the DMTPC detector concept. Right: two designs for the amplification region: “mesh-plate” (top) and “triple mesh” (bottom).

although it slightly degrades the sensitivity [6]. “Head-tail” discrimination is also very important as it improves the sensitivity for detecting DM by about one order of magnitude [6].

Due to the low-density of the target material, directional detectors tend to be large in volume: a typical directional detector with a fiducial mass of one ton occupies $\mathcal{O}(10^3)$ cubic meters. Therefore, the success of a directional DM program depends very strongly on the development of detectors with a low cost per unit volume. The largest expense for standard gaseous detectors is the cost of the readout electronics, making it essential to utilize low-cost readouts in order to make DM directional detectors financially viable.

2. The DMTPC detector concept

The DMTPC detector is a low-pressure TPC with optical readout. The detection principle is illustrated in Fig. 2, left. The TPC is filled with CF_4 at a pressure of about 50 torr. At this pressure, a typical 50 keV nuclear recoil has a length of about 2 mm. The average ionization energy in CF_4 is 54 eV [7], which results in about 10^3 primary electrons from the nuclear recoil. Such electrons drift toward the amplification region, where photons are produced together with electrons in the avalanche process. A CCD camera mounted above the cathode mesh records the image of the nuclear recoil projected along the amplification plane. The sense of the recoiling nucleus can be determined (“head-tail” discrimination), because the energy loss (dE/dx) is not constant along the trajectory. An array of photomultipliers (PMTs) mounted above the cathode mesh determines the length of the recoil in the drift direction through time measurements.

CF_4 was chosen as the target material primarily because of its high fluorine content. Fluorine is an excellent element to detect spin-dependent interactions on protons [8], due to its large spin factor and isotopic abundance (Table 1). Spin-dependent (SD) interactions are predicted to dominate over spin-independent ones in models where the lightest super-symmetric particle has a substantial Higgsino contribution [9, 10].

CF_4 is also an excellent detector material [11, 12]. Its good scintillation properties are very important for the optical readout. Our recent measurements [13] indicate that in CF_4 the number of photons produced between 200 and 800 nm wavelength is about 1 for every 3 avalanche electrons. Moreover, the low transverse diffusion characteristic of electrons in CF_4 allows for good spatial resolution in the reconstruction of the recoil track despite the long (25 cm) electron drift distance. Finally, CF_4 is non-flammable and non-toxic allowing for safe operation underground.

CCDs provide a true 2-D readout at a much lower cost-per-channel than any other readout technology used in particle physics. A modern low-noise CCD camera with 4 megapixels can be purchased today for a few thousand US dollars, which corresponds to 10^{-3} dollars/channel. The cost of a directional DM detector is dominated by the readout electronics, making the optical readout a solution toward an economically viable detector.

Two alternative implementations of the amplification region [14] are illustrated in Fig. 2. In the “mesh-plate” design (top) the amplification is obtained by applying a large potential difference ($\Delta V = 0.6\text{--}1.1$ kV) between a copper plate and a conductive woven mesh. A uniform distance of 0.5 mm between the plate and the mesh is ensured by the use of fishing wires spaced 2 cm apart. The copper or stainless steel mesh is made of $28\text{ }\mu\text{m}$ wire with a pitch of $256\text{ }\mu\text{m}$. The pitch of the mesh determines the intrinsic spatial resolution of the detector. The “triple mesh” design (bottom) yields a transparent amplification region, which enables a single CCD camera to image two drift regions, leading to a substantial cost reduction.

The DMTPC detector measures the number of photons in the CCD camera, the 2-D image of the recoiling nucleus, the distribution of energy loss along the recoil track, the width and integral of the PMT signal, and the electronic signal produced on the amplification plane.

The energy of the nuclear recoil is independently determined by the measurement of the number of photons observed in the CCDs, the integral of the electronic signal produced on the amplification mesh, and the integral of the PMT signal. The redundancy in the design is intentional and has the goal of maximizing the robustness of the measurement. The track length and direction of the recoiling nucleus are reconstructed by combining the measurement

Table 1. Spin of the nucleus J , nuclear spin factor $\lambda^2 J(J+1)$, and abundance in nature of various isotopes considered for SD-interaction studies. The figure of merit is defined as the product of the square of the nuclear mass, the number of isotopes per kg, and the spin factor.

Isotope	J	$\lambda^2 J(J+1)$	Natural abundance	Figure of merit
^{19}F	1/2	0.65	100%	74
^{23}Na	3/2	0.04	100%	6
^{73}Ge	9/2	0.06	7.8%	2
^{93}Nb	9/2	0.16	100%	91
^{127}I	5/2	0.01	100%	5
^{129}Xe	1/2	0.12	26%	25

of the projection along the amplification plane (from pattern recognition in the CCD) and the projection along the direction of drift (from the width of the signal recorded in the PMTs). The sense of the recoil track can be determined by the Bragg curve. The PMTs will also provide a measurement of the absolute z position of the recoil by measuring the time between the primary ionization and the amplified signal. This information will drastically reduce possible backgrounds from the amplification meshes.

The CCD images have a long (1–10 seconds) exposure. If during the exposure a trigger is generated by the PMT or the electronic readout of the amplification plane, the CCD is read out and the event is saved to disk. Otherwise, the CCD is reset, minimizing dead time.

The combination of the measurements described above is very effective in reconstructing the energy, direction, and sense of nuclear recoils from WIMPs. In addition, an excellent rejection of the e^- and α backgrounds can be obtained by combining the measurement of the energy and length of the recoil (see below).

3. R&D results: demonstration of directional detection

An ^{241}Am source that produces 5.5 MeV alpha particles is used as calibration source. The image of one alpha particle stopped inside CF_4 at 100 torr is shown in Fig. 3, left. Fig. 3, right, shows the Bragg curve for 5.5 MeV alpha particle in CF_4 at 280 torr. The histogram shows the energy loss measured in the prototype, while the solid line shows the results of a SRIM [15] simulation. The agreement between data and MC is better than 10%. The alpha source is used to study the gain of the detector as a function of the voltage in the amplification region and gas pressure, while a ^{55}Fe can be used for absolute energy calibration. The alpha source is also used to measure the resolution as a function of the drift distance of the primary electrons to quantify the effect of the diffusion. Our studies [16] show that the transverse diffusion has $\sigma < 1$ mm for a drift distance of 25 cm.

The first demonstration of the DMTPC detector concept was obtained with a small chamber that used parallel wire planes to obtain charge amplification. This detector was used to perform the first observation of the “head-tail” effect in nuclear recoils generated by low-energy neutrons [16]. The determination of the sense and direction of nuclear recoils was evaluated by studying the recoil of fluorine nuclei in interactions with low-energy neutrons. For nuclear recoils below 1 MeV only the tail of the Bragg peak is visible, and therefore the energy deposition decreases along the path of the recoil, allowing for the identification of the “head” (“tail”) of the event by a smaller (larger) energy deposition. This initial measurement used 14 MeV neutrons

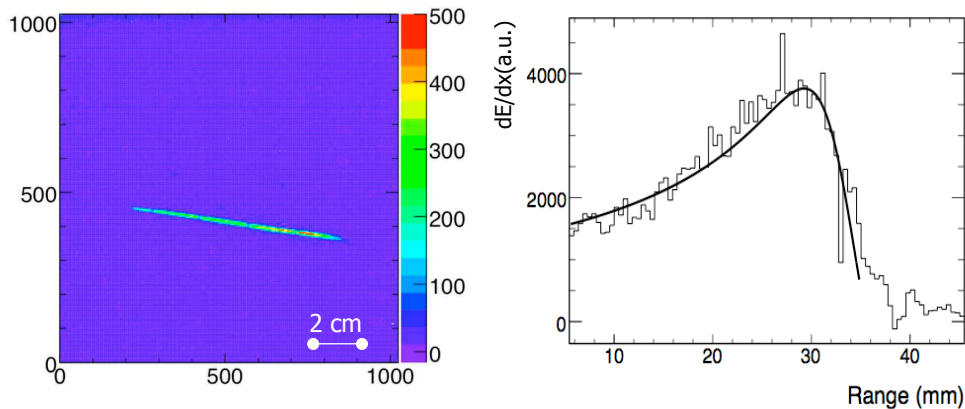


Figure 3. Left: an α track stopped in CF_4 at 100 torr (direction: left to right). Right: average light yield vs. range of the α tracks in data (histogram) compared to the SRIM MC prediction [15].

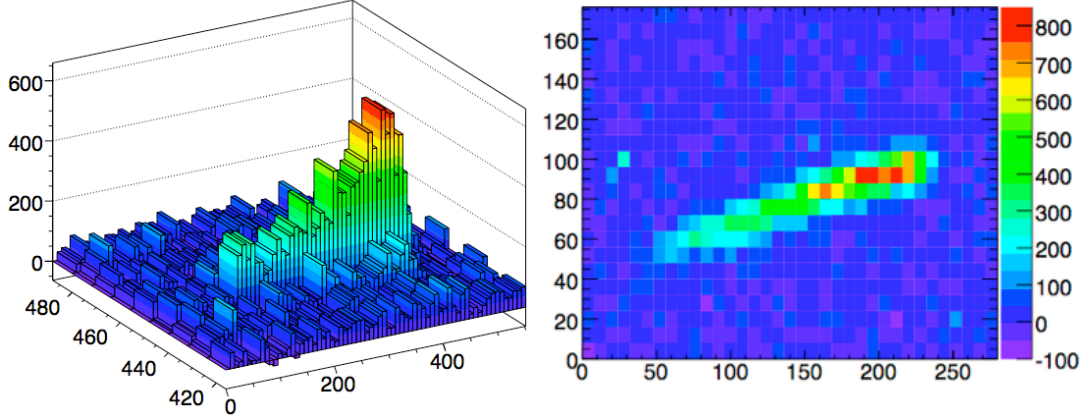


Figure 4. Left: nuclear recoil from a 14 MeV neutron in CF_4 at 250 torr recorded with the wire-based DMTPC prototype. Right: nuclear recoil induced by a neutron from a ^{252}Cf source in CF_4 at 75 torr. In both cases the neutrons were traveling right to left. The higher dE/dx visible on the right of the track is consistent with observation of the “head-tail” effect.

from a D-T generator. The reconstructed recoils had energy between 200 and 800 keV. The energy distribution along the recoil track for one of such recoils is shown in Fig. 4, left. We measured that $(73 \pm 3)\%$ of the recoils had the correct sense. This measurement represents an observation of the the “head-tail” effect with a significance of 8σ [16].

A newer mesh-based detector was later used to study the “head-tail” effect in lower energy neutrons generated by a ^{252}Cf source. This detector allowed us to obtain a 2-D reconstruction of the nuclear recoils. Better sensitivity to lower energy thresholds was achieved by lowering the CF_4 pressure to 75 torr. Fig. 4, right shows a Cf-induced nuclear recoil due to a neutron traveling right to left inside our detector. The decreasing dE/dx along the track direction clearly visible in the image proves that the detector is able to determine the sense of the direction on an event-by-event basis. Measurements of the track length as a function of the recoil energy and of the recoil angle are shown in Fig. 5. The data (black dots) are in good agreement with the predictions of the SRIM [15] MC (histogram). Our recent measurements [14] demonstrated “head-tail” discrimination down to 100 keV at 75 torr. Monte Carlo studies indicate that this effect can be observed for recoils above 50 keV at a pressure of 50 torr when using Apogee U6 CCD cameras.

The current DMTPC prototype consists of two optically independent regions contained in

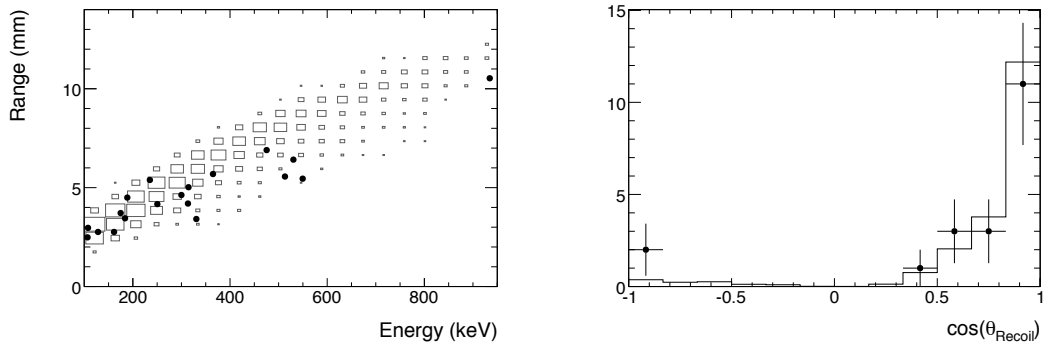


Figure 5. Range vs. reconstructed energy (left) and signed cosine of the recoil angle (right) of nuclear recoil candidates from ^{252}Cf at 75 torr. Black points are data; histogram is simulation.

one stainless steel vessel. Each region is a cylinder with 25 cm diameter and 25 cm height. A field cage made of stainless steel rings keeps the uniformity of the electric field within 1% in the fiducial volume. The amplification is obtained by using a “mesh-plate” design (Fig. 2, top-right). The detector is read out by two CCD cameras, each imaging one drift region. The optical system consists of two Nikon photographic lenses with f-number of 1.2 and focal length of 55 mm, and two Apogee U6 CCD cameras [17] equipped with Kodak 1001E CCD chips. Because the total area imaged is $16 \times 16 \text{ cm}^2$, the detector has an active volume of about 10 liters.

4. DMTPCino detector design

DMTPCino is a 1-m^3 DMTPC detector designed to substantially improve limits on spin-dependent interactions of WIMPs on protons while testing the DMTPC detector concept on a larger scale and in a realistic environment. The preliminary design of the detector is shown in Fig. 6. The apparatus consists of a stainless steel vessel of 1.3 m diameter and 1.2 m height. Nine CCD cameras and nine PMTs are mounted on each of the top and bottom plates of the vessel, separated from the active volume of the detector by an acrylic window. The detector consists of two optically separated regions. Each region is equipped with a triple-mesh amplification device, mounted in between two symmetric drift regions. Each drift region has a diameter of 1.2 m and a height of 25 cm, for a total active volume of 1 m^3 . A field cage keeps the uniformity of the electric field within 1% in the fiducial volume. A gas system circulates and purifies the CF_4 .

All materials used inside the active volume of the detectors are selected to be radio-pure to limit backgrounds from internal radioactivity. Pure copper, stainless steel, Ph bronze, Vesper, quartz and acrylic are known to satisfy these requirements [18]. Because all CCD cameras, lenses, and PMTs are outside the active volume, their contribution to internal radioactivity is negligible.

At a pressure of 50 torr and 21 degrees C, this module will contain 250 g of CF_4 . Assuming an overall data-taking efficiency of 50%, a one-year run will yield an exposure of 45 kg-days.

The CCD cameras we plan to use for DMTPCino are the same Apogee Alta U6 that we are currently using on the 10-liter detector. The U6 uses a Kodak Grade 2 KAF-1001E (1024×1024 pixel array, each pixel $24 \times 24 \mu\text{m}^2$) full-frame sensor with peak quantum efficiency of 72% at 560 nm, and a readout noise of 13 (20 max) electrons.

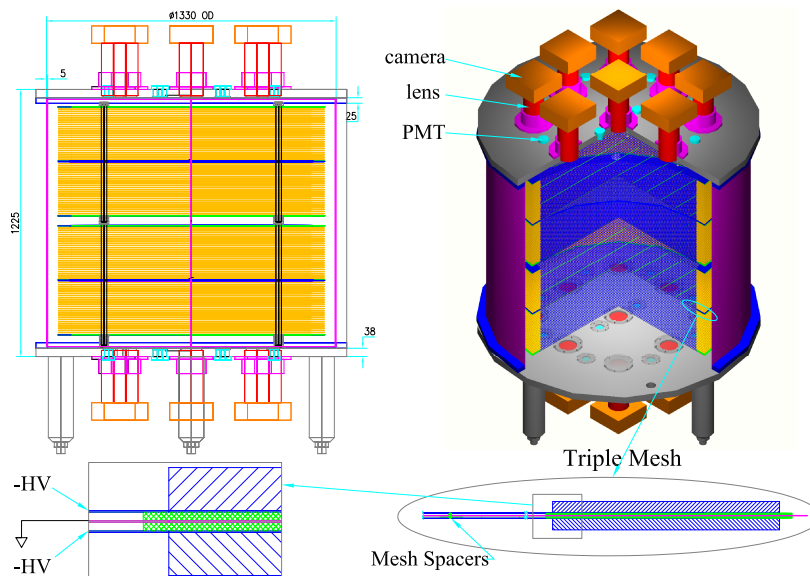


Figure 6. Preliminary drawings of the 1 m^3 DMTPC detector.

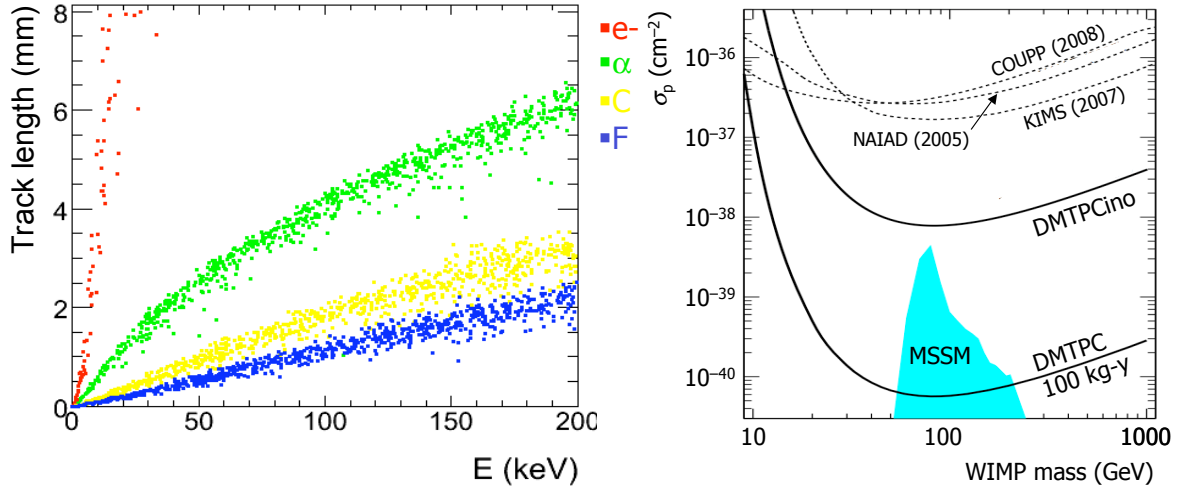


Figure 7. Left: range versus energy of the recoil track for fluorine recoils (blue), carbon recoils (yellow), alphas (green), and electrons (red). Right: expected 90% C.L. limits on SD interactions of WIMPs on protons for DMTPCino (top solid line) and a larger DMTPC detector (bottom solid line). The dashed lines show the best present limits. The blue area shows the MSSM expectation.

5. Background suppression

The main source of background for a DMTPC detector, as for any DM experiment, is due to electromagnetically interacting particles such as photons and electrons, and to α particles. These particles are produced by natural radioactivity of the detector components and surrounding materials, as well as by cosmic rays. The impact of these backgrounds will be substantially suppressed by using only radio-pure materials in the fabrication of the apparatus and by shielding the detector. In addition, the directional information provides a powerful signature that can be used to distinguish particle species: the correlation between the energy and length of the recoil track.

Fig. 7, left, shows the distribution of the length versus energy of the track expected in the DMTPC detector for electrons (red), alpha particles (green), and carbon (yellow) and fluorine (blue) nuclear recoils from WIMP interactions. The MC simulation used is known to reproduce current data within 10%. From this plot, we conclude that an excellent discrimination against α particles can be achieved with a threshold of 30 keV or lower. The gamma ray rejection factor, measured using a ¹³⁷Cs source, is better than 2 parts per million.

Neutrons backgrounds will be reduced by operating the detector underground and making use of a passive shielding. Residual neutrons will be rejected using the directional information.

Directionality is also key to distinguish between WIMP signal and coherent scattering of solar neutrinos, which will point back to the sun.

6. Expected sensitivity from DMTPCino

The sensitivity of the DMTPCino detector to SD interactions of WIMPs on protons has been studied assuming that the detector will be operated at a threshold of 30 keV¹ in an underground laboratory at a depth < 1,600 m.w.e., and that it will be surrounded by a neutron shielding consisting of 40 cm of polyethylene. No significant internal backgrounds are assumed to be present above threshold. The limits expected from DMTPCino (5 months of data-taking at

¹ Assuming a quenching factor of about 55% for recoils of 50 keV, as predicted in reference [19], a 30 keV threshold in the detector corresponds to a nuclear recoils with kinetic energy of 50 keV.

50% efficiency) are shown in Fig. 7, right. Improvements of a factor of 50 over the best existing measurements [20, 21, 22] can be obtained despite the limited target mass due to the large SD cross-section of fluorine (Table 1) and to the excellent background rejection capability of the detector.

A large DMTPC detector, with an active mass of 10^2 – 10^3 kg, will be able to explore a significant portion of the Minimal Supersymmetric Standard Model (MSSM) parameter space [10] (Fig. 7, right). Such a detector is an ideal candidate for the DUSEL laboratory.

7. Conclusion

The DMTPC detector is designed to measure the energy, position, direction, and sense of low-energy nuclear recoils generated by a WIMP interaction. The combination of the energy and tracking information allows for an efficient suppression not only of backgrounds due to electrons, photons, and alphas, but also of more insidious backgrounds, such as neutrons and neutrinos. The choice of gas (CF_4) makes this detector particularly sensitive to spin-dependent interactions. We estimate that with a 1-m^3 detector (DMTPCino) in less than one year of data-taking underground we will be able to improve the existing limits on SD interactions on protons by about a factor 50. Such a detector will lay the foundation for the design of a large directional DM detector that could provide an unambiguous positive observation of WIMPs as well as a way to discriminate between the various galactic DM halo models.

8. Acknowledgments

This work was supported by the Advanced Detector Research Program of the U.S. Department of Energy, the National Science Foundation, the Pappalardo Fellowship program, the MIT Kavli Institute for Astrophysics and Space Research, and the Physics Department at the Massachusetts Institute of Technology.

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